Los Alamos LDRD Workshop

Neutrino Energy Reconstruction

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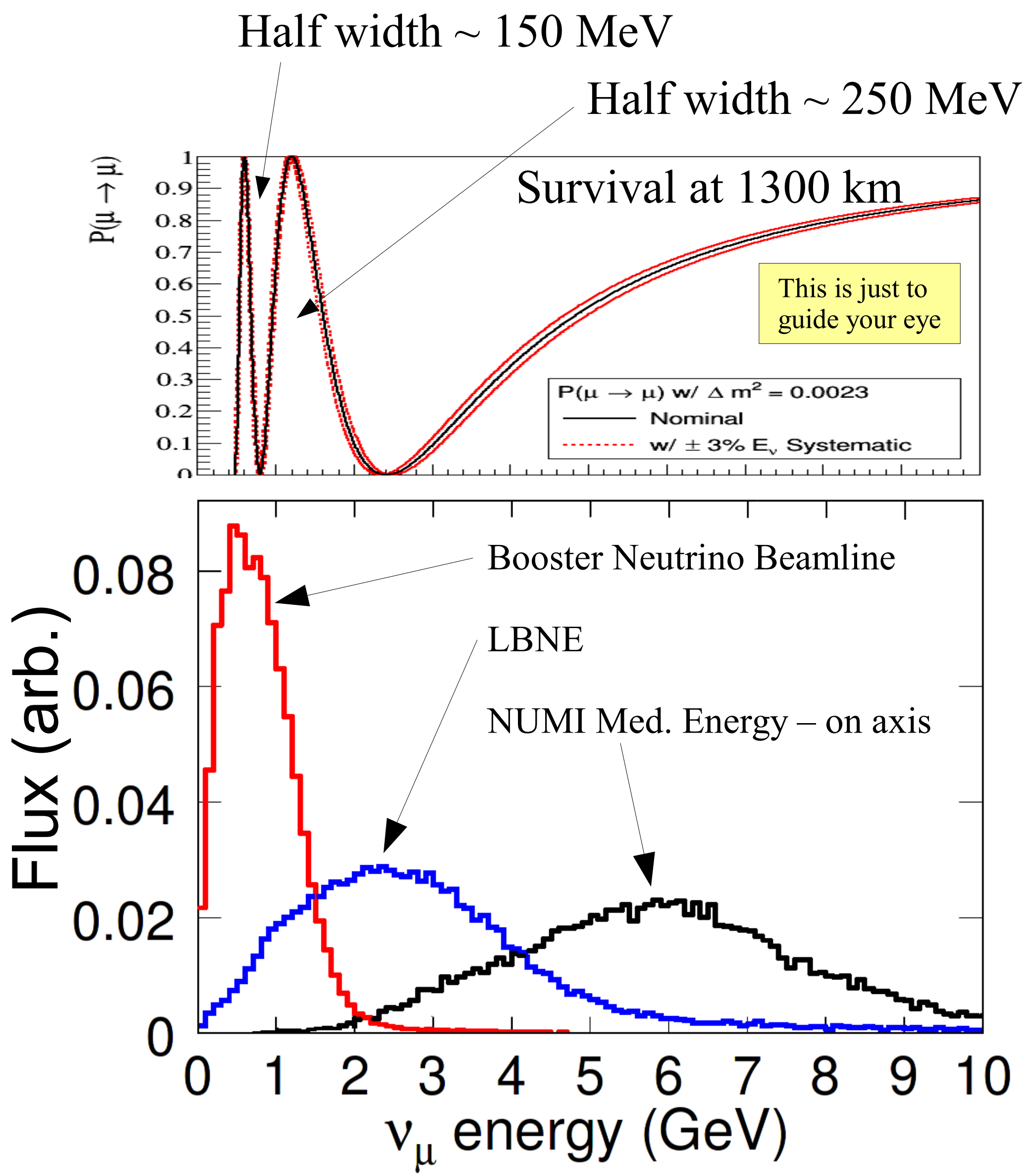
E_ν Reconstruction: An Inverse Process

- Want to find the flux after the distortion from oscillations
  - Measure a distribution of neutrino interactions
  - Find the flux by unfolding the efficiency and cross section
- The efficiency needs to be constrained by calibration
- The cross section is constrained by measurement, but depends on model
  - The produced final states provoke different detector responses so the differential cross sections are needed for energy reconstruction.
- In an oscillation experiment
  - The near detector flux used to measure the cross section is very different from the far detector flux.
  - Cross section modifications that introduce asymmetries in the energy reconstruction can hide in the near detector data
    - I'll give an explicit example later when I discuss T2K

Typical LBNE Neutrino Flux

- Need to observe multiple nodes to break degeneracies
  - 1^{st} osc. is 2 GeV to 3 GeV
  - 2^{nd} osc. is 500 MeV to 1 GeV
- E_ν resolution gives ability to find features
  - Half widths of osc. features
    - First Max: 20%
    - Second Min: 18%
- E_ν scale gives ability to locate features
  - For $\delta(\Delta m^2) \sim <1 \times 10^{-4}\ eV^2$
    - $\delta(E_\nu)$ << 5%
      - for ν_e and ν_μ
    - Absolute energy << 5%
      - for all particles



Neutrino CC Cross Sections

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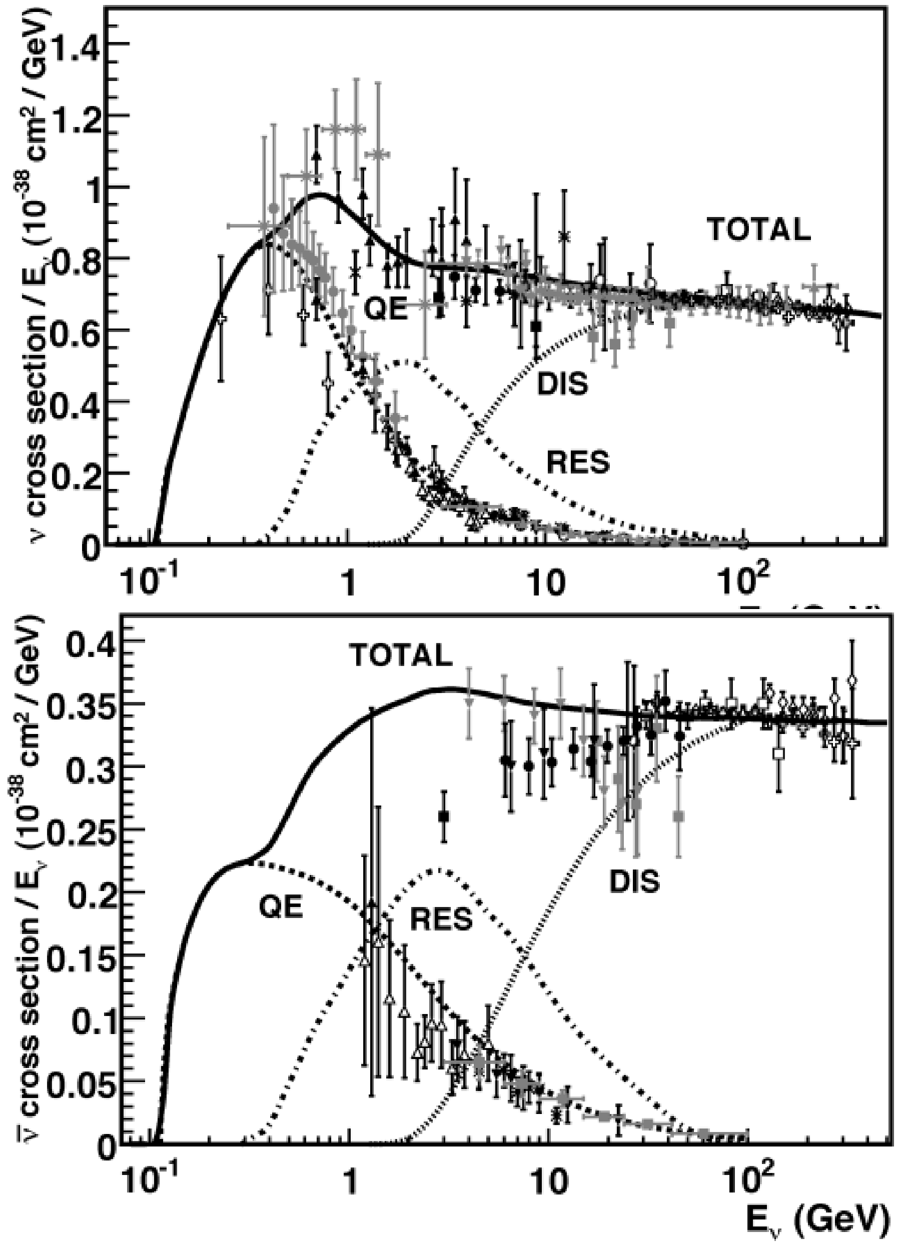
- Above 10 GeV: Dominated by DIS
  - Simple cross-section to calculate
  - Very little dependence on nucleus
- Below 10 GeV: Interesting...
  - Interplay between several different branches
    - QE (below 1 GeV)
    - Several Resonant scattering modes
- Care must be taken to define the neutrino measurements in terms of observables, not cross section models
  - e.g. Charged current w/o pions vs CC quasi-elastic scattering

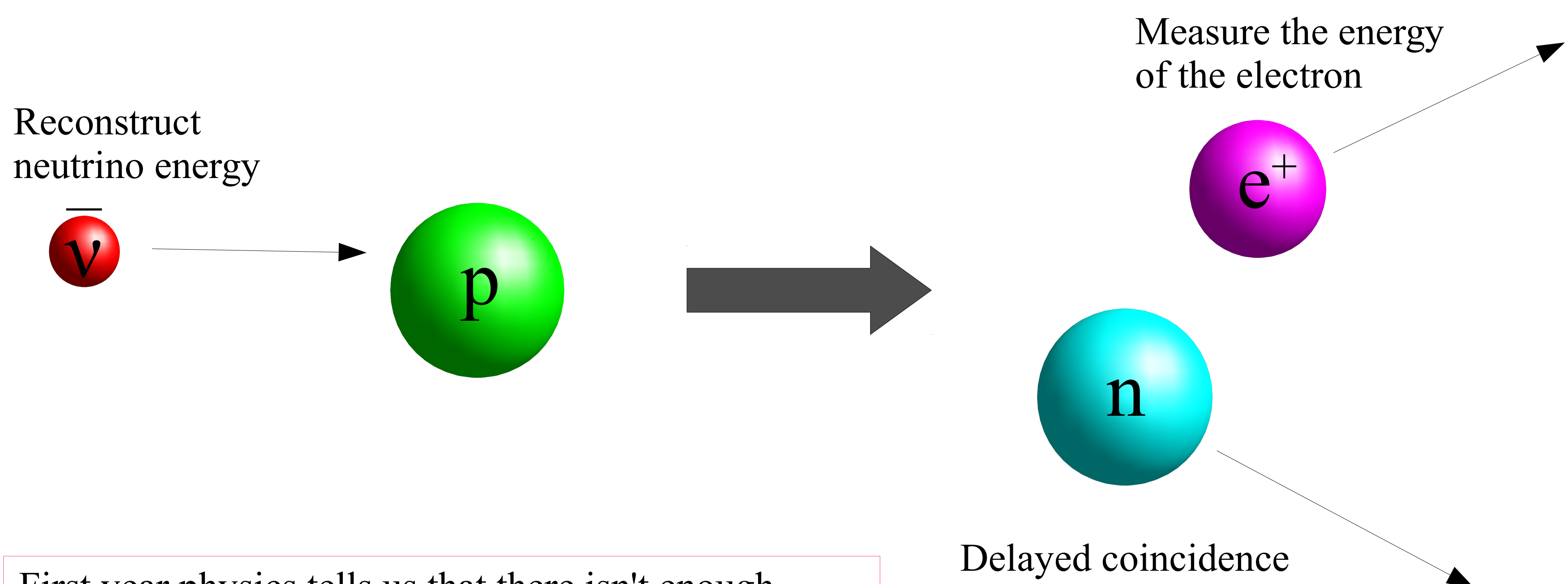


Reconstructing E_ν

- Neutrino physics is based on "nothing in, something out"
  - The problem is to find the energy of "nothing" (the neutrino)
    - without knowing the initial state of the target (needs a model).
    - without knowing if all final state particles are observable (needs a model).
    - without knowing if the final state particles scatter before being observed (needs a model).
- Kinematic Reconstruction
  - e.g. Neutrino Energy assuming CCQE
- Calorimetric Reconstruction
  - Neutrino Energy from E_{vis}.
  - Inverse Beta Decay (low energies)
  - $E_\nu = E_l + E_{had}$ (high energies)

Example 1: Inverse Beta Decay

- Appropriate since Reines and Cowan pioneered this at LANL



First year physics tells us that there isn't enough information to reconstruct the collision.

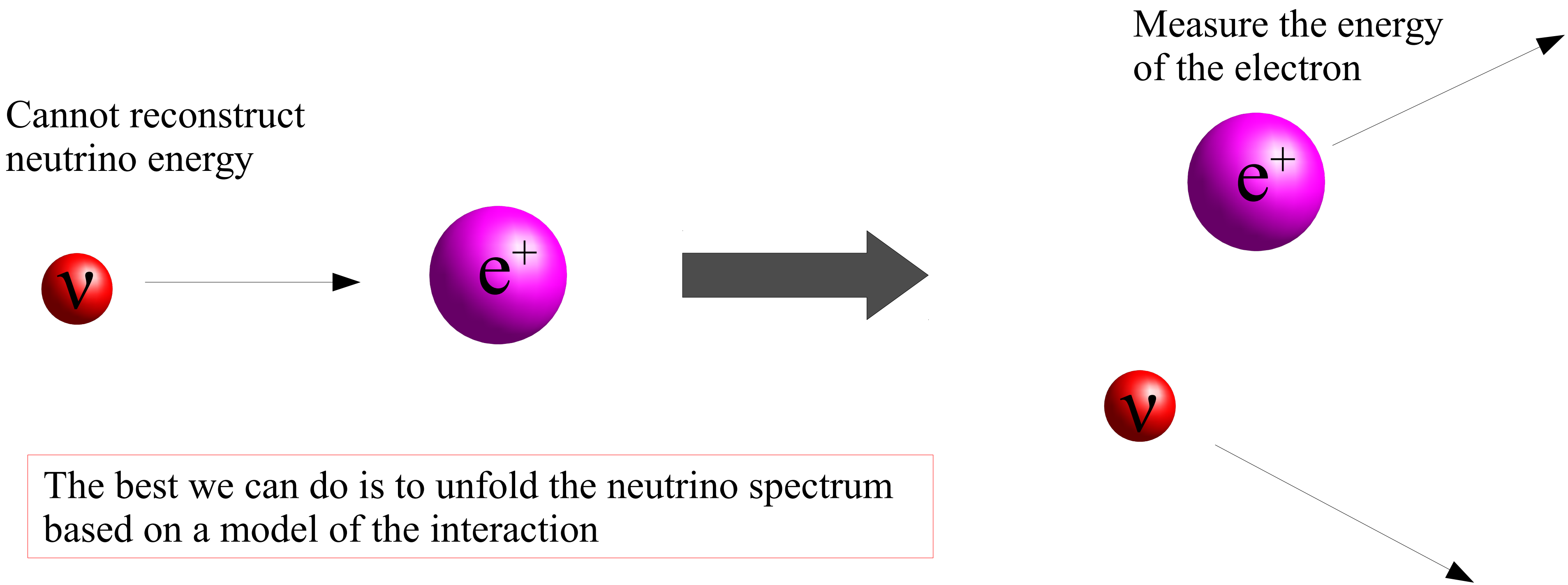
An Energy Reconstruction Problem

- We don't have enough information to reconstruct the incoming neutrino kinematics
- For inverse beta decay
  - Assume the interaction is on a proton
  - Assume the only products are
    - a positron (we see the deposited energy)
    - a neutron (we see a delayed coincidence)
  - That's still not enough information
    - Assume the proton starts at rest
    - Assume the neutron is “infinitely massive”
- With those assumptions the neutrino energy is
  - The positron total energy
    - Correct energy for annihilation on an electron
  - plus the change in nucleon mass

Model dependent assumptions are needed to reconstruct the neutrino energy

Example 2: Neutrino Elastic Scattering

- Obvious truism
  - If we don't know enough about the outgoing products, then we can't reconstruct the neutrino energy

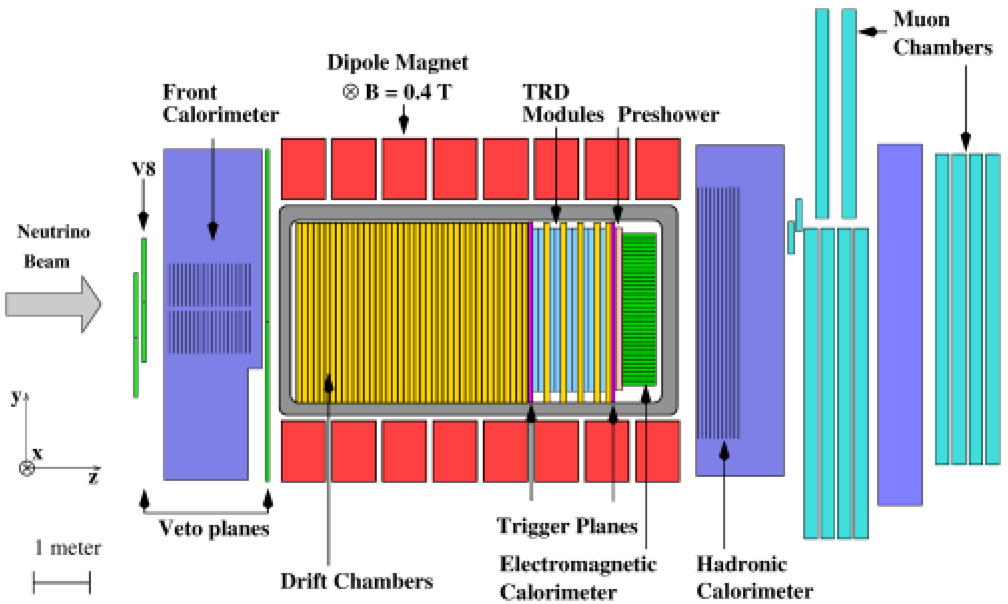


The best we can do is to unfold the neutrino spectrum based on a model of the interaction

Observations for Experiments

- Determining the neutrino energy requires an interaction model
  - We (usually) don't know the target kinematics.
  - We (often) don't see all of the products.
- Sometimes, even when we have a model, there isn't enough information to reconstruct the neutrino energy.
  - The honest statement would be: “Usually, even when...”
- In general, neutrino energy isn't reconstructed
  - Again, neutrino energy distributions are “unfolded” based on
    - Models of the neutrino interactions
    - Models of the detector performance

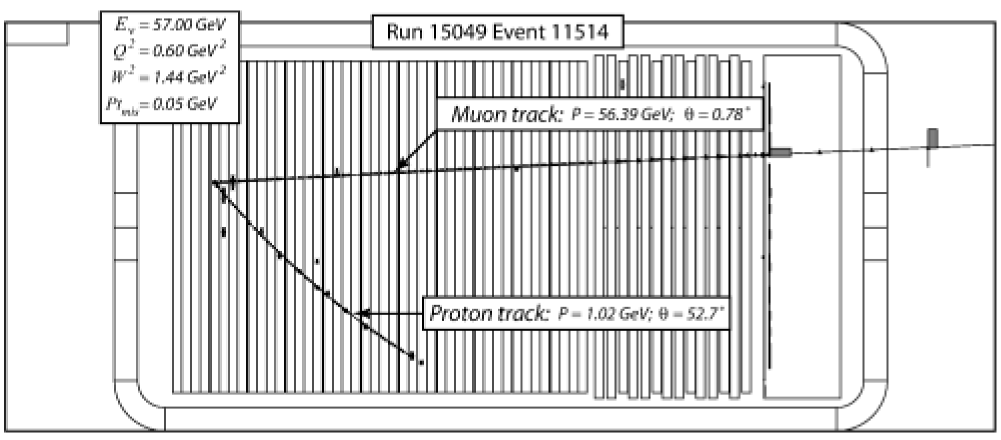
NOMAD as an Ideal



The next few slides are going to pick on NOMAD

Because of the beam energy and granularity it as very good particle reconstruction capabilities

Average neutrino energy: 24.3 GeV
Active target composition:
64% C, 22% O, 6% N, 5% H, 3% other
Active target density: ~0.1 gm/cm^3.
Drift chamber hit efficiency: ~95%



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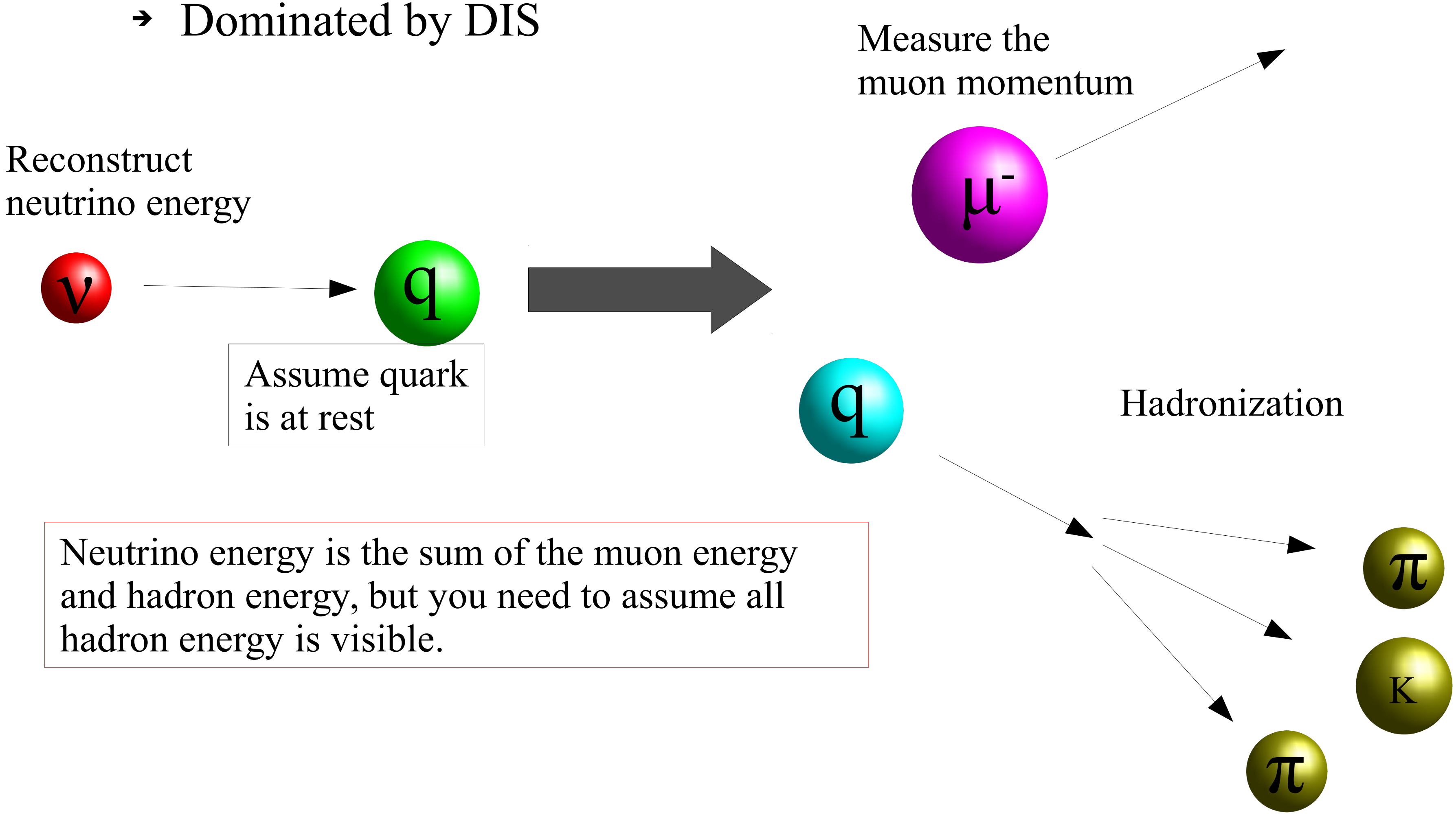
Example 3: NOMAD (E_ν >2.5 GeV)

- The NOMAD inclusive cross section measurements calculate the neutrino energy as the total energy visible in the detector.
  - Dominated by DIS



Neutrino energy is the sum of the muon energy and hadron energy, but you need to assume all hadron energy is visible.

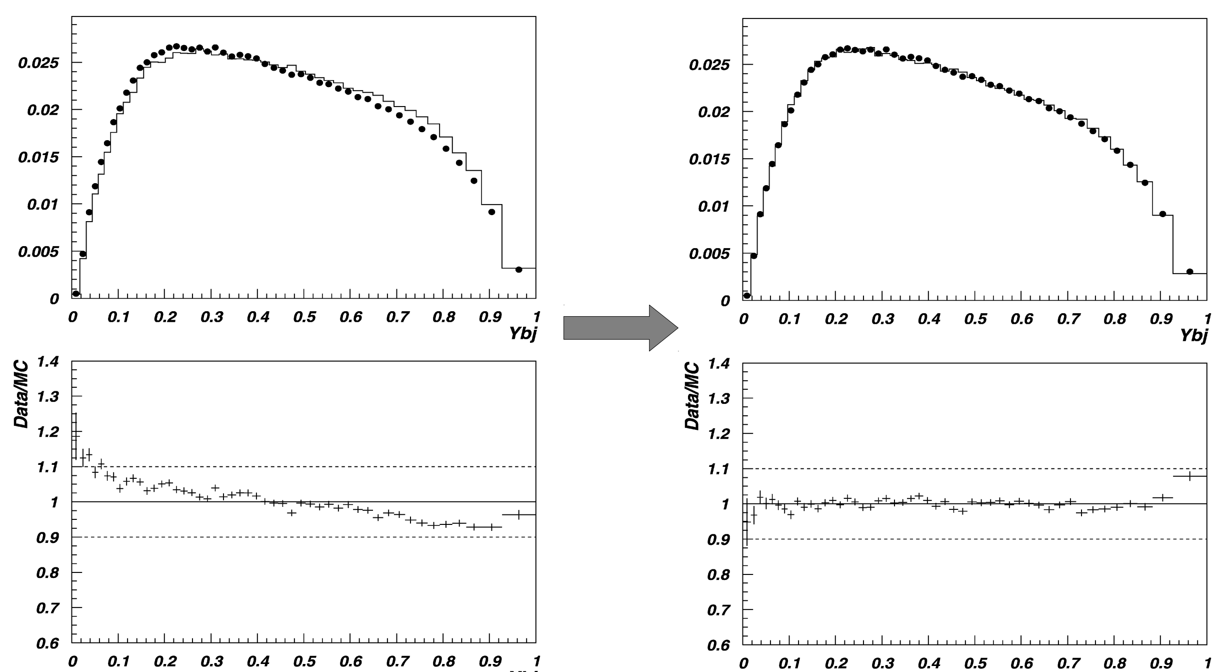
Calorimetric Neutrino Energy

- If all of the products of the neutrino interaction are visible, then the neutrino energy is equal to the sum
  - Typical NOMAD neutrino energy resolution: about 15%
- Assumes initial conditions are known and all outgoing energy is collected.
  - Can be checked by looking for missing transverse momentum
- Must model quark hadronization
  - If you assume that the neutrino flux is well understood, then the hadronization model can be tuned.

Tune MC assuming the differential cross section correctly predicts

$$Y_{B_i} = \frac{E_{had}}{E_\nu} = \frac{E_{had}}{\left(E_{had} + E_\mu\right)}$$

This works for DIS



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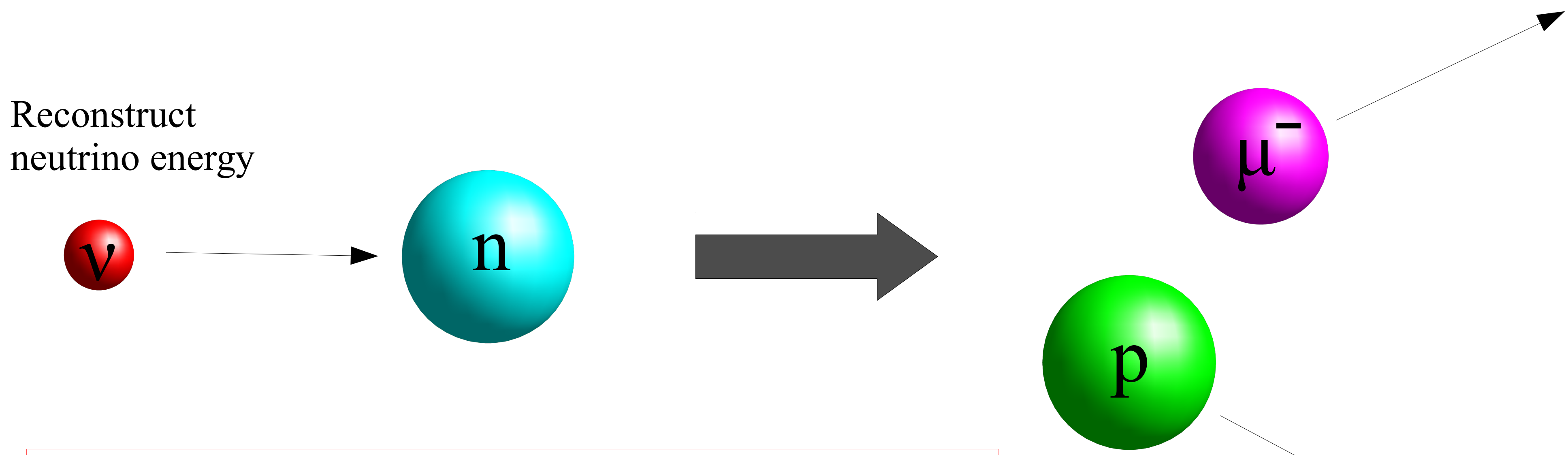
Example 4:
NOMAD Final State Reconstruction

- For exclusive final states, the neutrino energy can be reconstructed by fully reconstructing the final state.
- Average $E_\nu \sim 25$ GeV



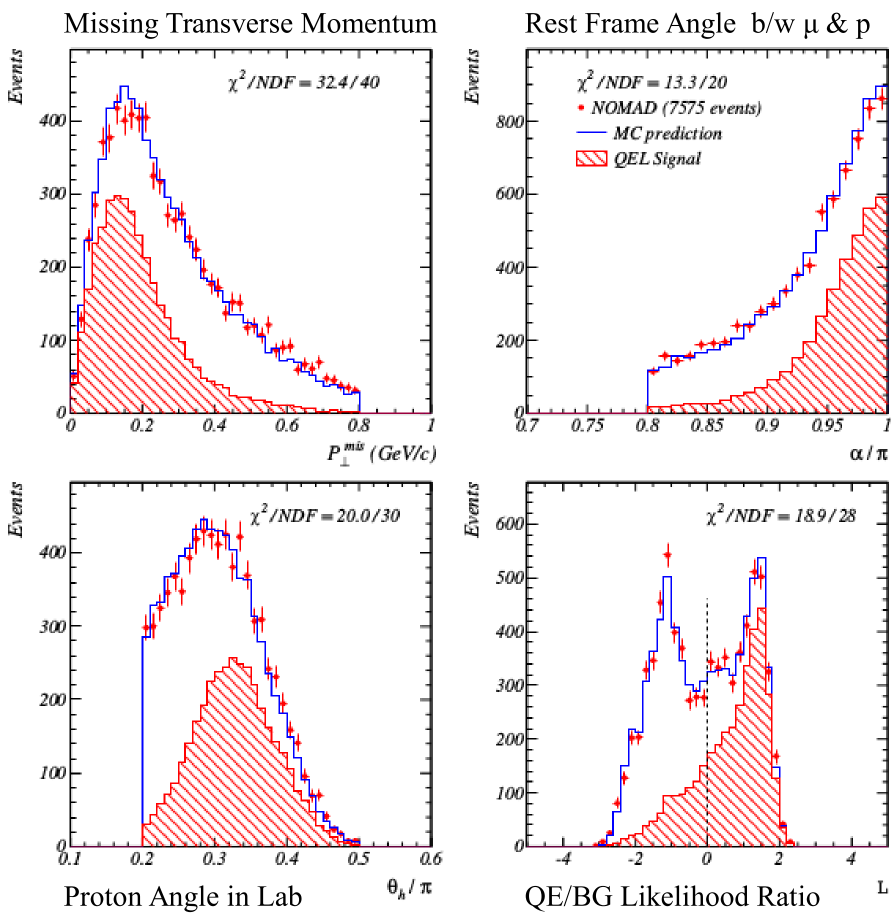
The collision is with a nucleus, but
- assume the target is a "free" neutron at rest.
- assume the rest of the nucleus can be ignored.

Final State Reconstruction

- Even if the final state is fully reconstructed, to get the neutrino energy we need to know target kinematics
  - If our target or interaction channel assumptions are wrong, then the neutrino energy is not correctly reconstructed
  - For large neutrino energies, this is less of a concern
- Final state interactions will effect the resolution
  - We know the neutrino direction, so we can determine the missing transverse momentum
    - Gives constraint of missing particles, initial state conditions, final state interactions and reconstruction resolution
- We need to fully reconstruct the final state
  - If particles are missed, then the neutrino energy is incorrectly reconstructed.

NOMAD Background

(two track sample)



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- After selecting muon and proton
  - Efficiency: 17.6%
  - Purity: 47.2%
- Cut on kinematic likelihood
  - Efficiency: 13.3%
  - Purity: 73.9%
- Note that the kinematic likelihood includes one of the variables used to reconstruct E_ν
  - Potential to sculpt the shape of the E_ν and Q^2 distributions

NOMAD QE Reconstruction Resolution ($E_\nu \sim 25$ GeV)

- For QE signal events, the neutrino energy resolution will be determined the measurement resolutions
- Very high resolution!
  - But this doesn't account for any background contribution
  - Compare to about 15% for inclusive neutrino energy.

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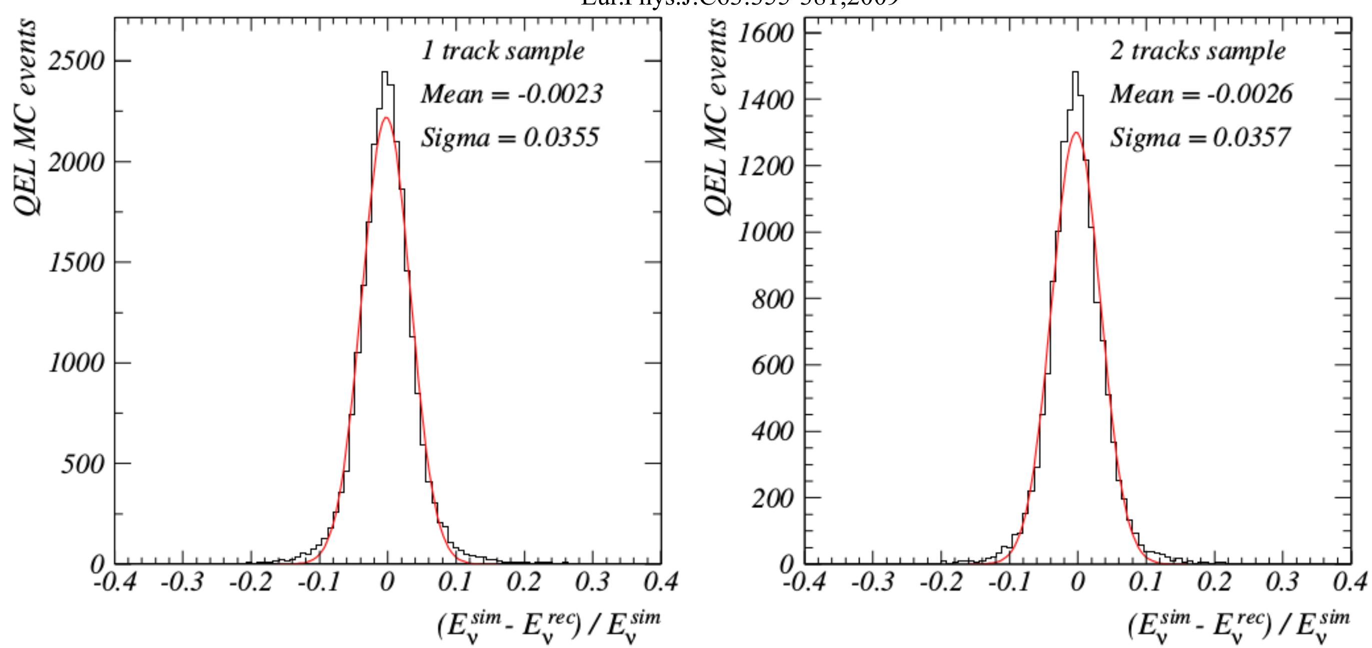


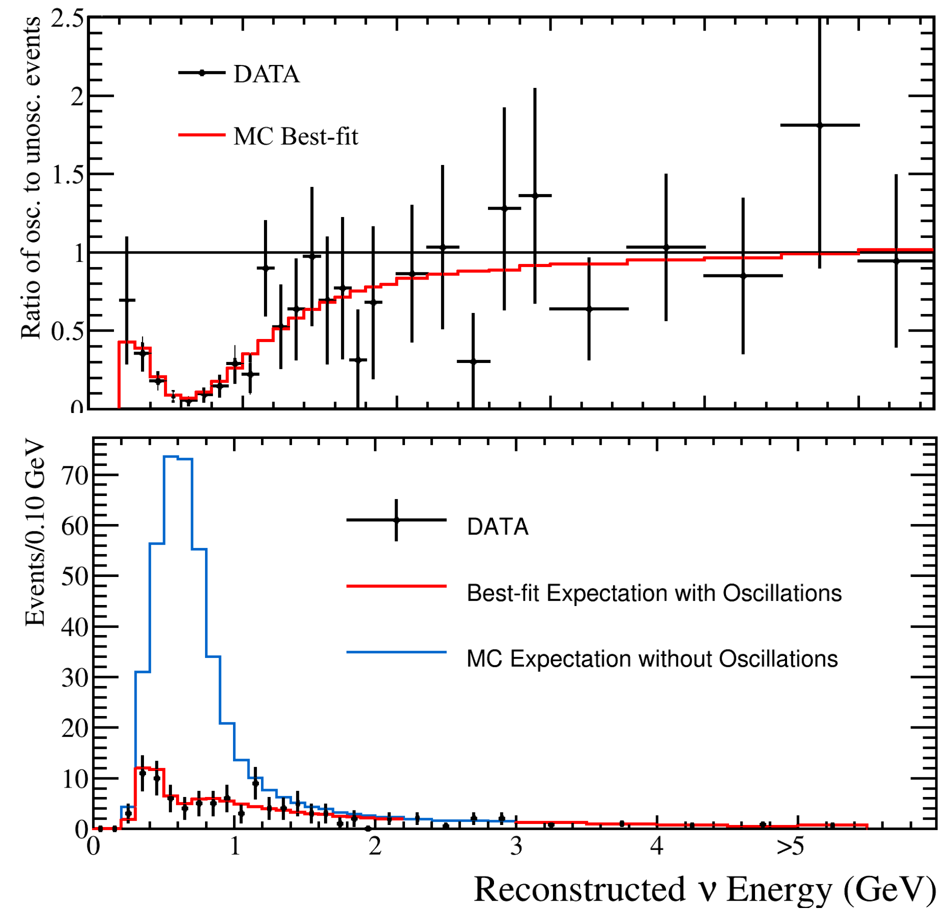
$$E_\nu = \frac{M_n E_\mu - m_\mu^2}{M_n - E_\mu + P_\mu \cos\theta_\mu}$$

$$E_\nu = p_\mu \cos\theta_\mu + p_p \cos\theta_p$$

Oscillations and Neutrino Energy

Case Study: T2K ν_μ Disappearance

- Ability to reconstruct neutrino energy directly impacts the ability to determine oscillation parameters.
  - A 5% shift in neutrino energy gives a 5% shift in Δm^2
- The shape of the energy resolution also has an affect
  - Long tails affect the ability to measure the mixing angles.
  - Fundamental limit from Fermi momentum in nucleus.



T2K 2013 disappearance result

The T2K ν_μ Energy Range

- Flux largely is below 1 GeV
  - Cross section dominated by CCQE
- Analyze using a charged current with no pion sample.
  - Sample defined by the observables, not the model
  - Contributions from several cross section channels
- Reconstruct neutrino assuming the target is a neutron
  - $\nu_\mu + n \rightarrow \mu^- + p$ (no pions)
    - Assume neutron is at rest
    - Reconstruct energy from μ^- kinematics
- Correct for assumptions using a neutrino cross section model

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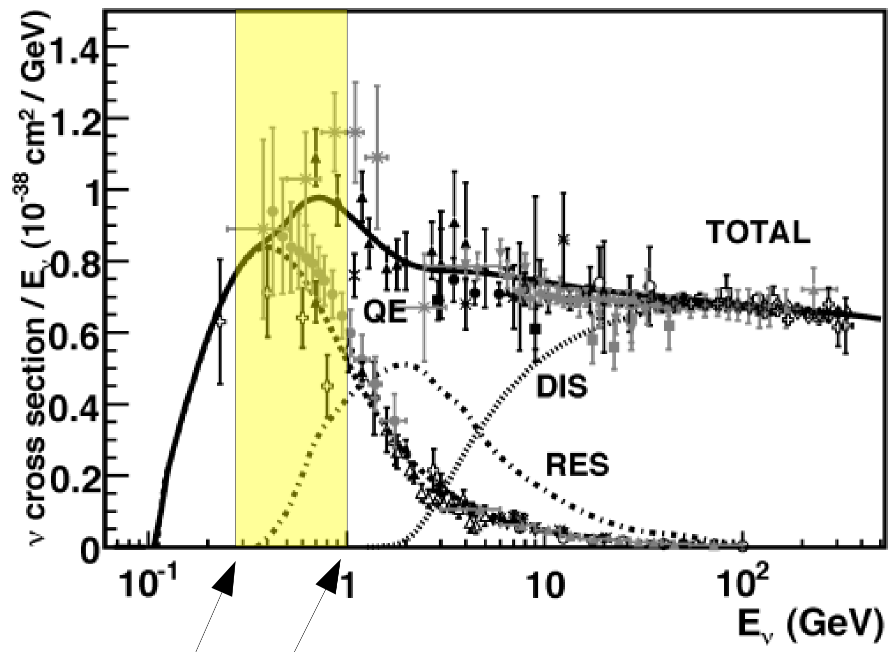
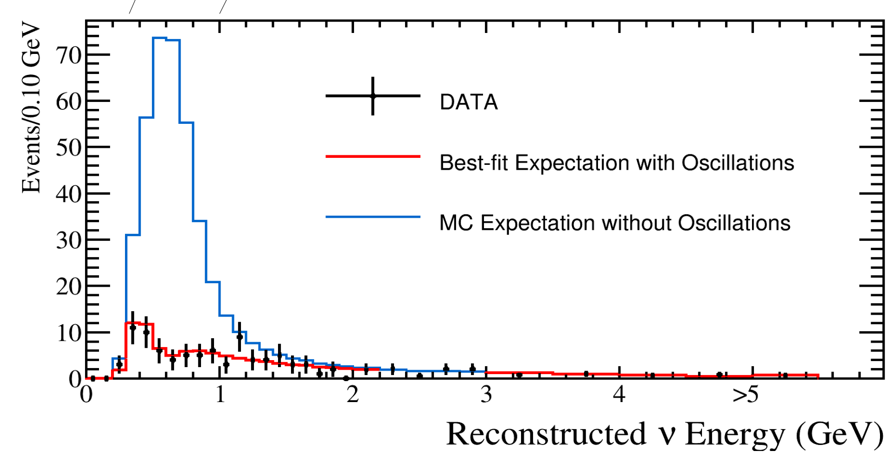
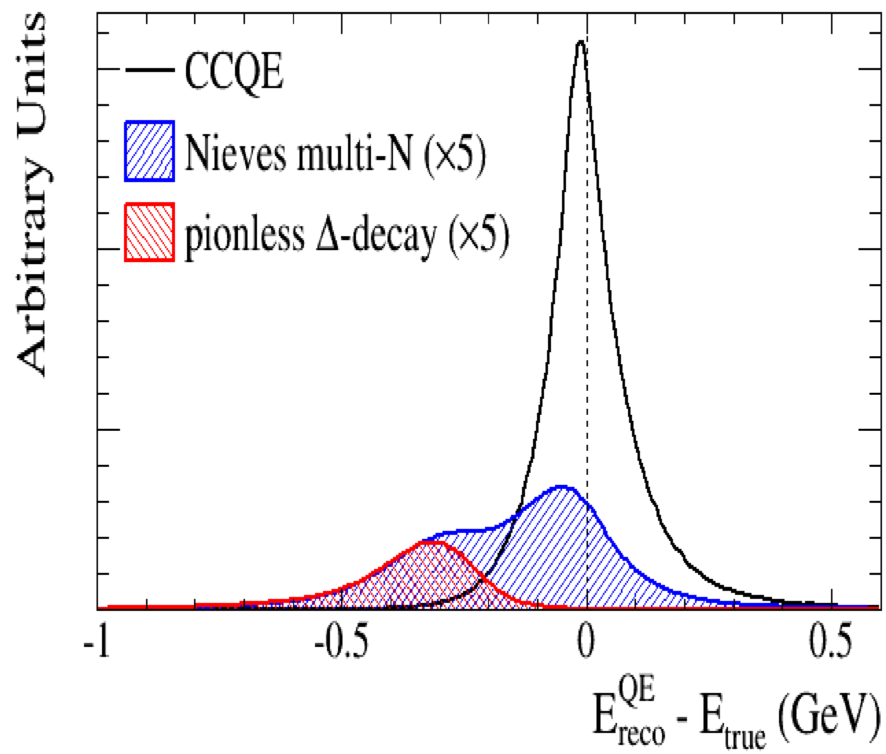




Complications...

- Initial state of the target
  - Fermi Gas
  - Spectral Function
- Charged charged current quasi-elastic is not the only mode which will produced a single lepton with no pions
  - Resonant scattering with pion absorption
    - Pionless Δ – decay
  - Multi-nucleon effects
- Final state interactions
  - Charge exchange
  - Absorption
  - Rescattering

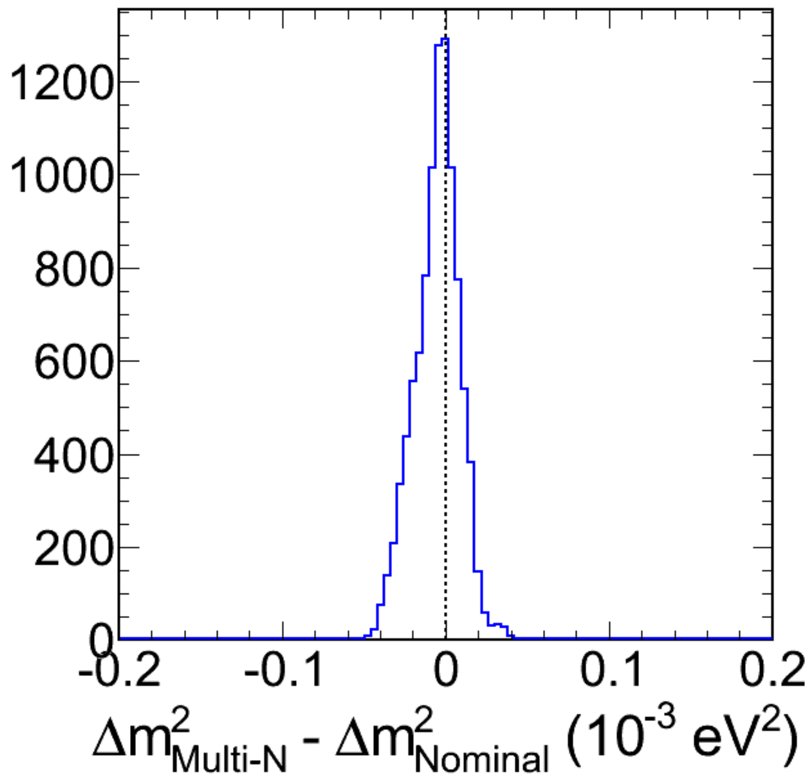


Examples of different models and the effect on the reconstructed energy.

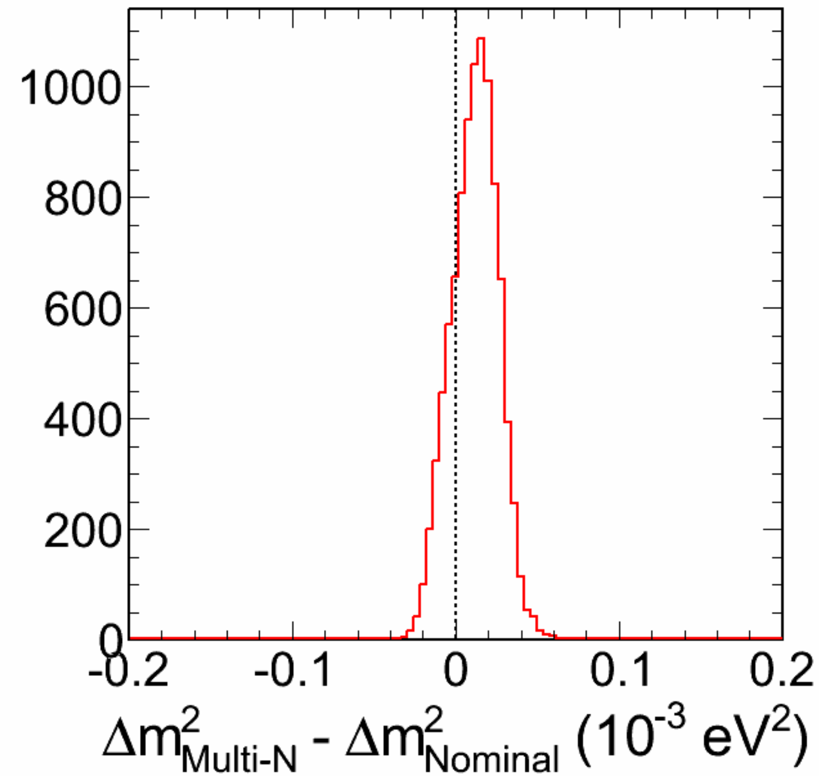
Bias introduced into the reconstructed neutrino energy.

Effect on Reconstructed Δm^2

- Interactions in the nucleus are complex with different models predicting different neutrino energy reconstruction
  - More neutrino interaction modeling is needed
  - More neutrino interaction measurements are needed to evaluate the models



Nieves 2p-2h model

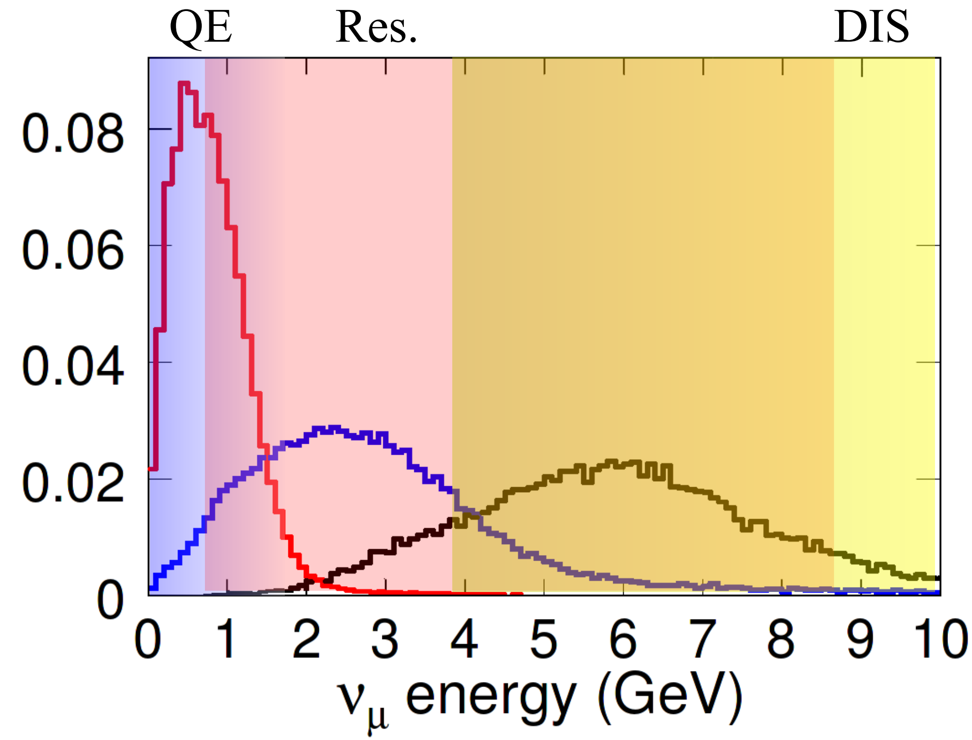


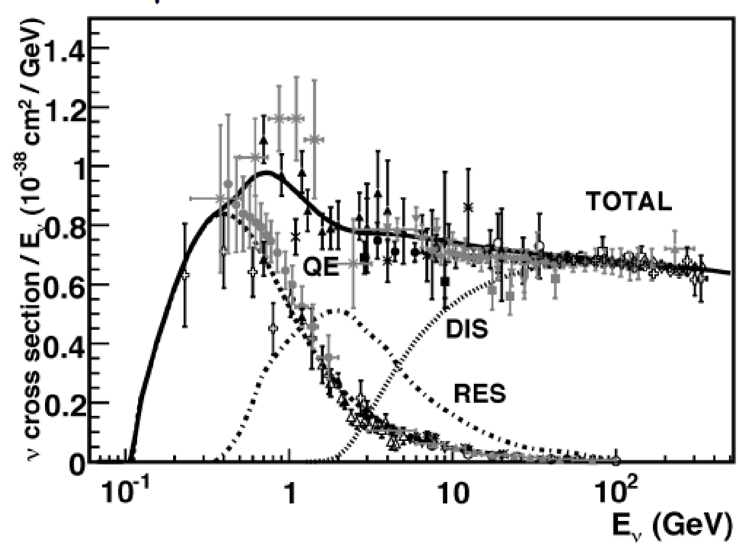
Martini MEC model

This model uncertainty alone limits Δm^2 resolution to about 3%

LBNE E_ν Reconstruction

- The LBNE wide band beam spans an interesting range of neutrino cross sections
  - High energy tail measured using DIS
  - First oscillation measured using resonant scattering
  - Second oscillation at transition between QE and resonant scattering.
- Few existing argon neutrino cross section measurements
  - Expect significant FSI and nuclear corrections
- Will need to tie many effects together to predict E_ν response





Kinematic Reconstruction

- Example Signature
  - Single charged lepton (e or μ)
    - Momentum from range or ionization deposit
  - No pions
  - Any number of nucleons
- Can also be done for resonant scattering
  - Pion collision length: ~70 cm
    - Pions usually scatter before ranging out.
- Complications (as seen with T2K)
  - Argon is a large nucleus
    - Nuclear FSI
    - Pauli Blocking
    - etc
  - Assumes the target is a nucleon
    - But nucleus is more complicated than that.
  - Reconstruction is tied to the understanding of the cross section
    - Also a small part of the total cross section at higher energies
  - Needs strong assumptions about the neutrino direction and target.
- Advantages
  - Simple well defined topology in the detector
  - High precision – Only depends on the (well measured) lepton

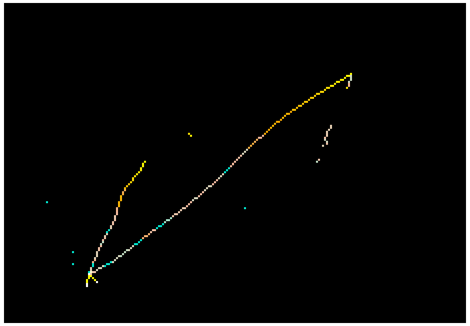
Calorimetric Reconstruction

- Neutrino energy estimated from the total visible energy
- Uses an inclusive signature
  - Charged lepton
- Advantages
  - Uses the full CC sample
  - Less sensitive to the cross section mode
    - But the partial cross sections for different final states will affect the corrections
  - Don't need to assume the neutrino direction.
- Complications
  - Sensitive to invisible energy
    - Neutrons, energy lost to mass
  - Sensitive to the hadronic secondary interaction models
  - Corrections are energy dependent.

Some Event Simulations

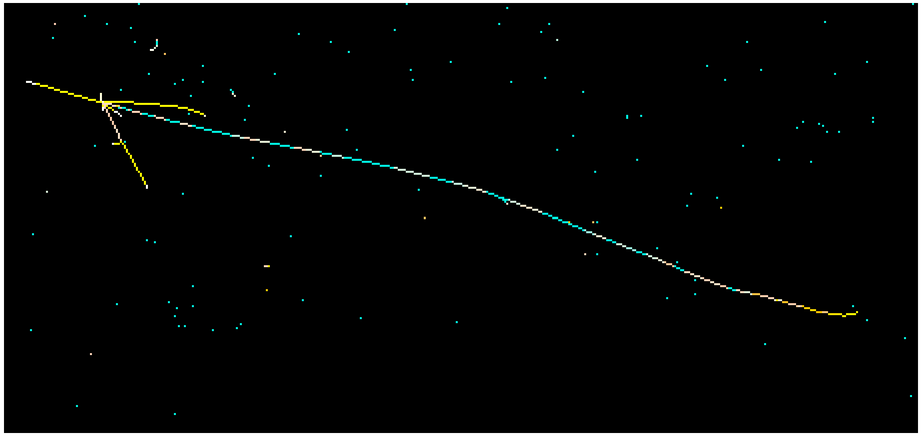
- Simple simulation to illustrate scale of corrections required to reconstruct neutrino energies in Liquid Argon
  - G4 based “detector” simulation
    - Large, essentially infinite volume of liquid argon
    - Simulate the energy deposition of charged particles
      - “Birk's Law” simulation turned off for these simulations
        - In a full simulation and reconstruction, this is a substantial correction
  - GENIE for neutrino interaction simulations
    - Mono energetic muon neutrinos
- Take the simulations at face value
  - This highlights a couple of issues.

Typical LBNE Neutrino Interactions

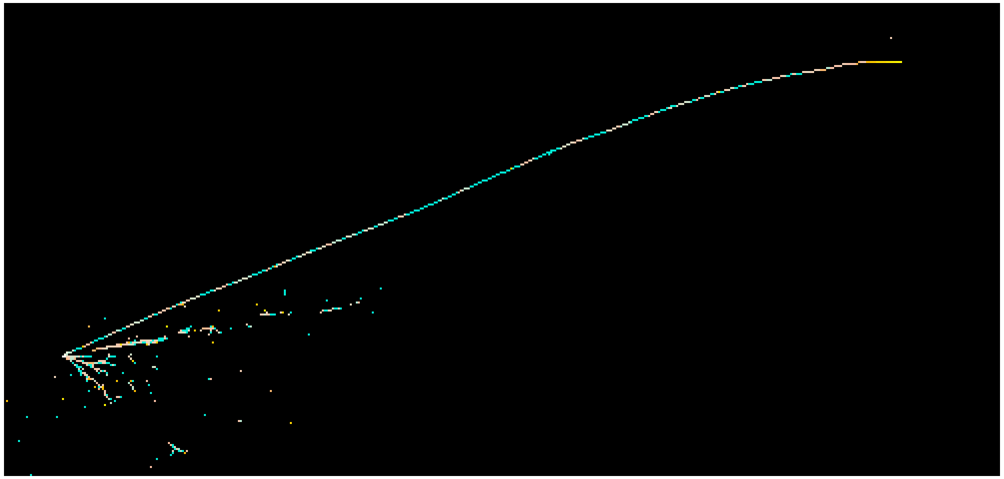


1 GeV

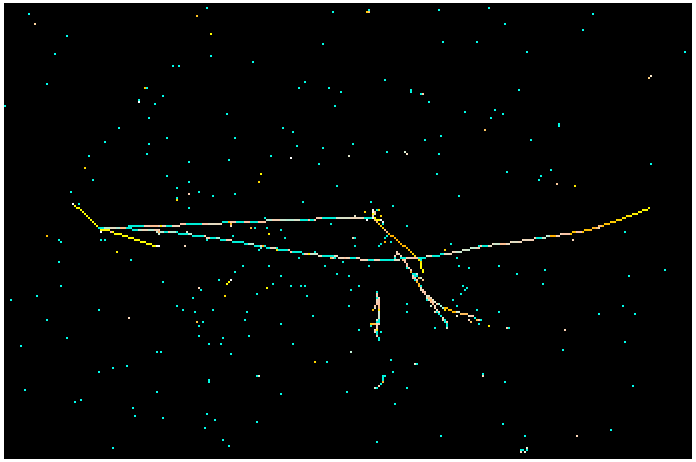
Energy deposition by charged particles from muon neutrinos.



2 GeV



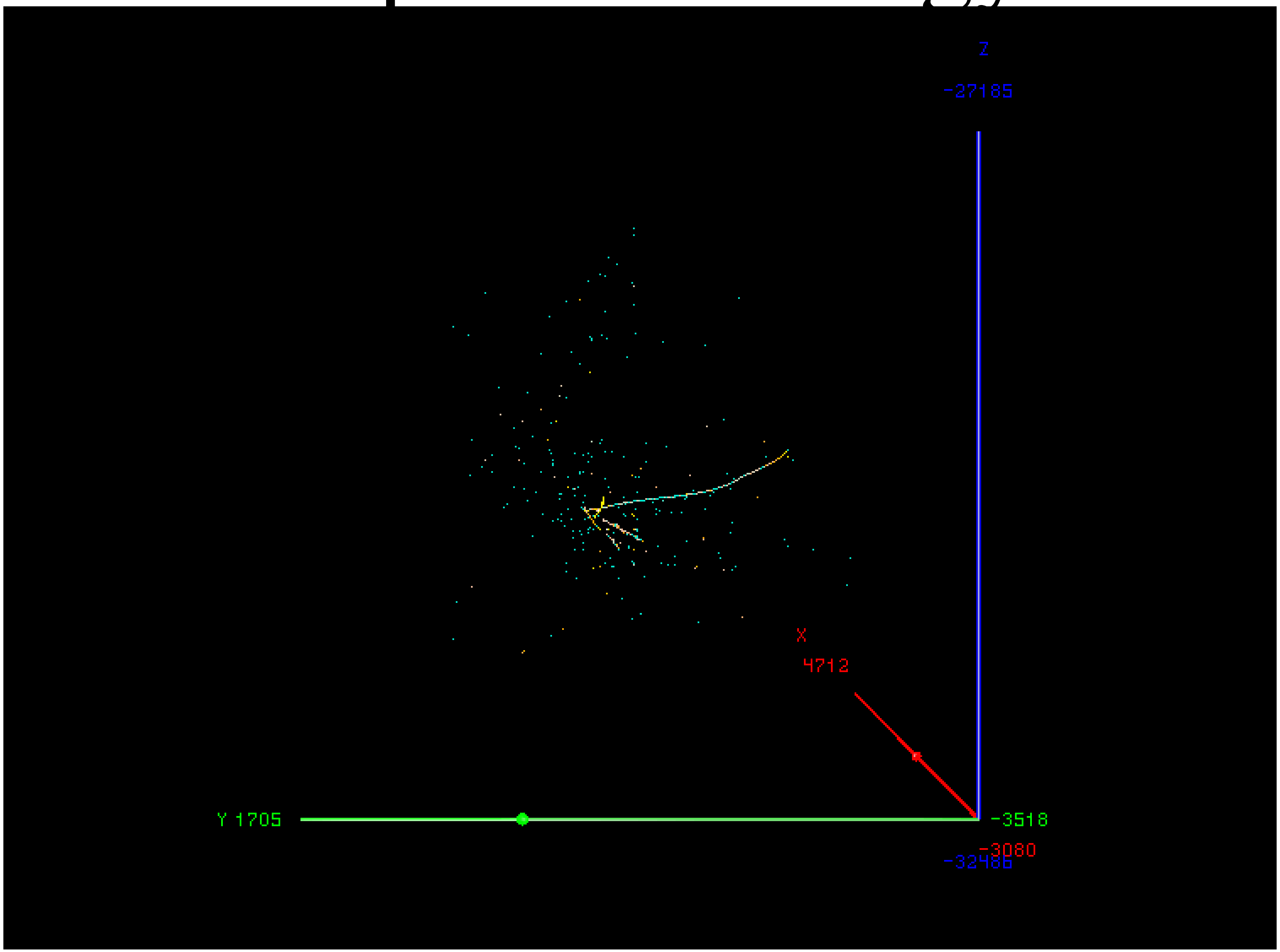
3 GeV



4 GeV

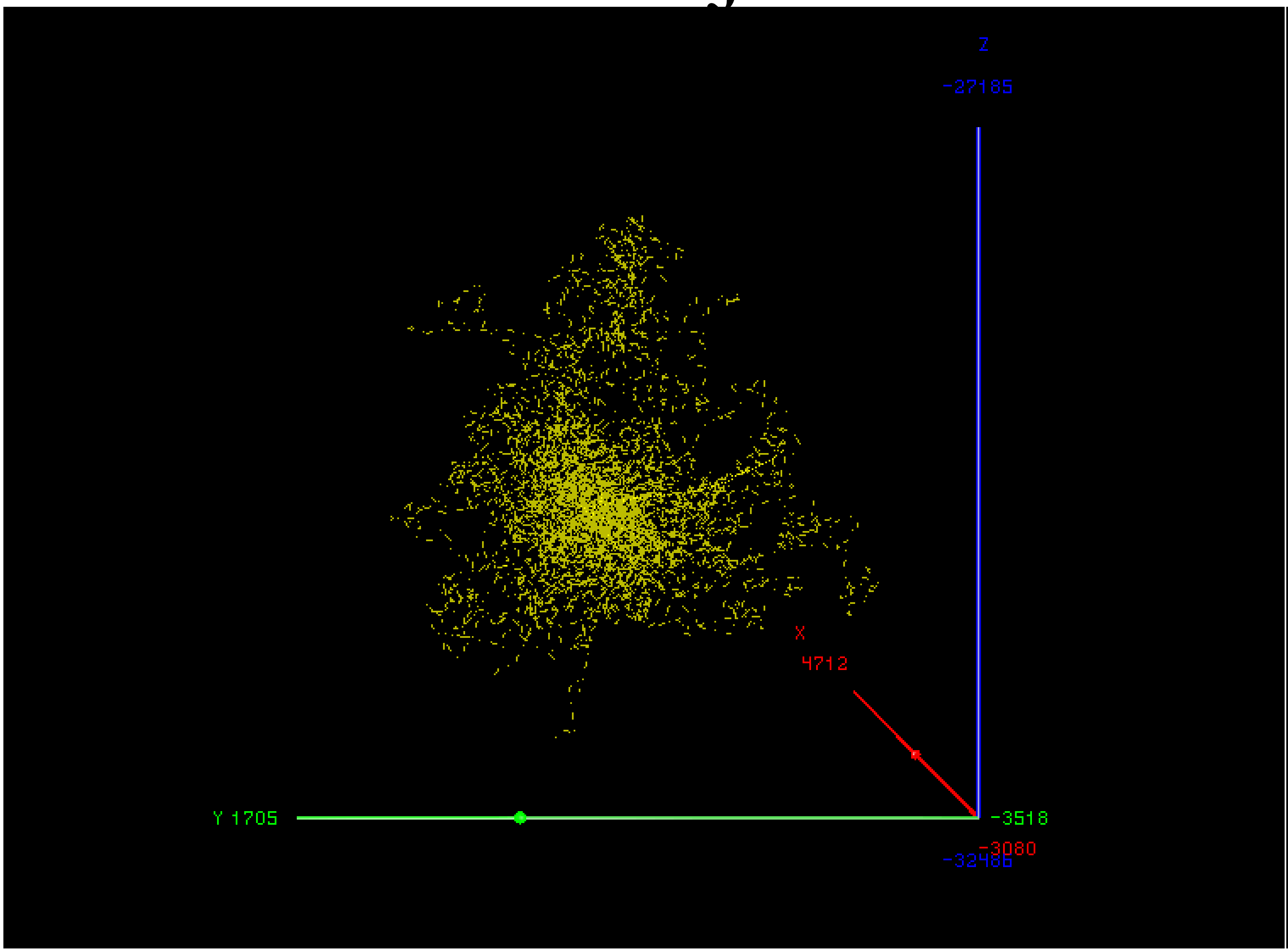
ν_μ beam is horizontal from the left to the right

Typical 4 GeV ν_μ Interaction: Deposited Energy



ν_μ beam is into the slide

Typical 4 GeV ν_μ Interaction: Particle Trajectories



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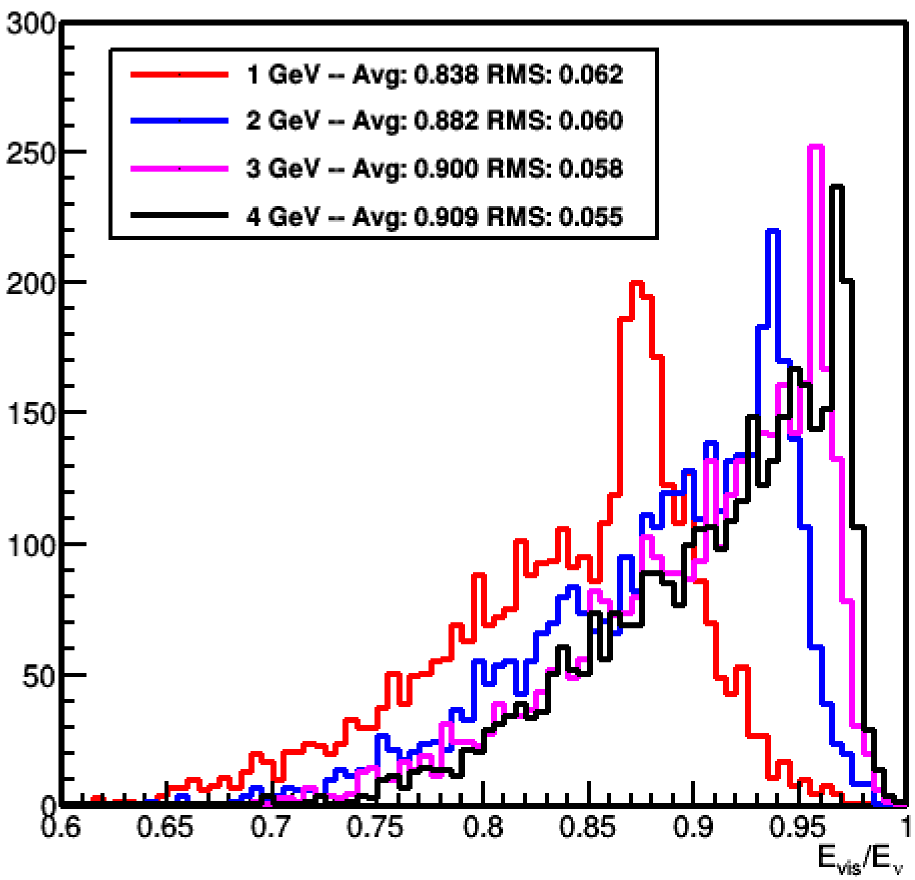
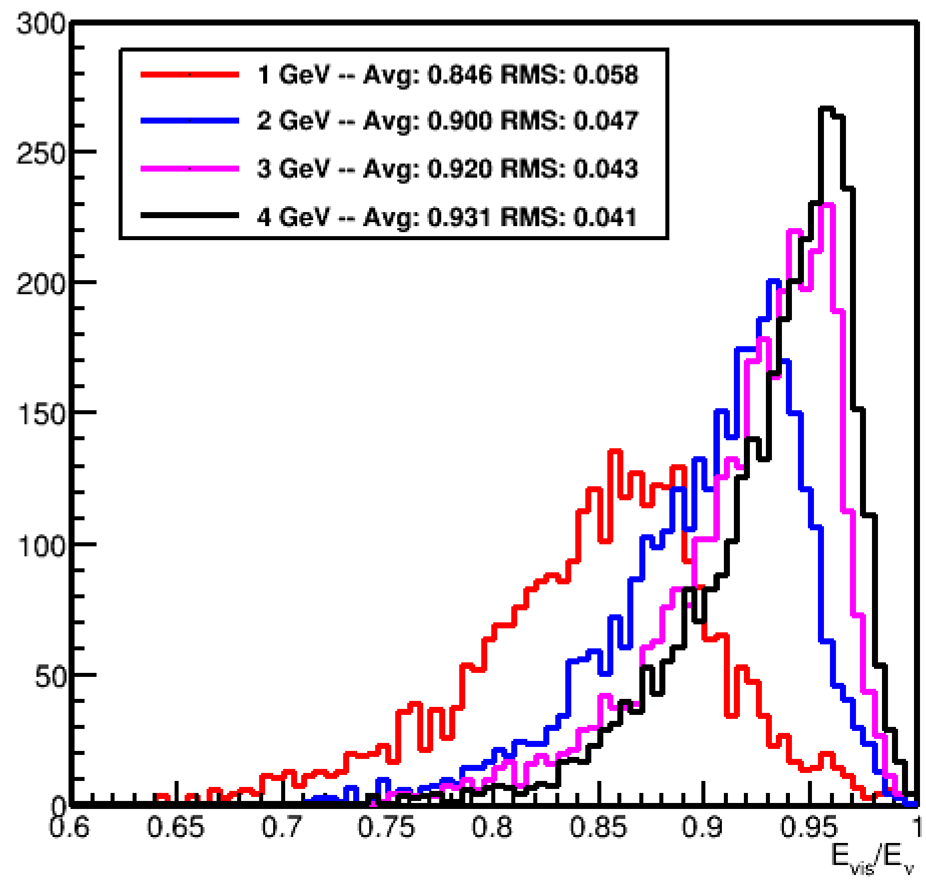
Fraction of E_ν that is Visible

- The ratio of visible energy to neutrino energy is different for neutrinos and anti-neutrinos

Muon Neutrino



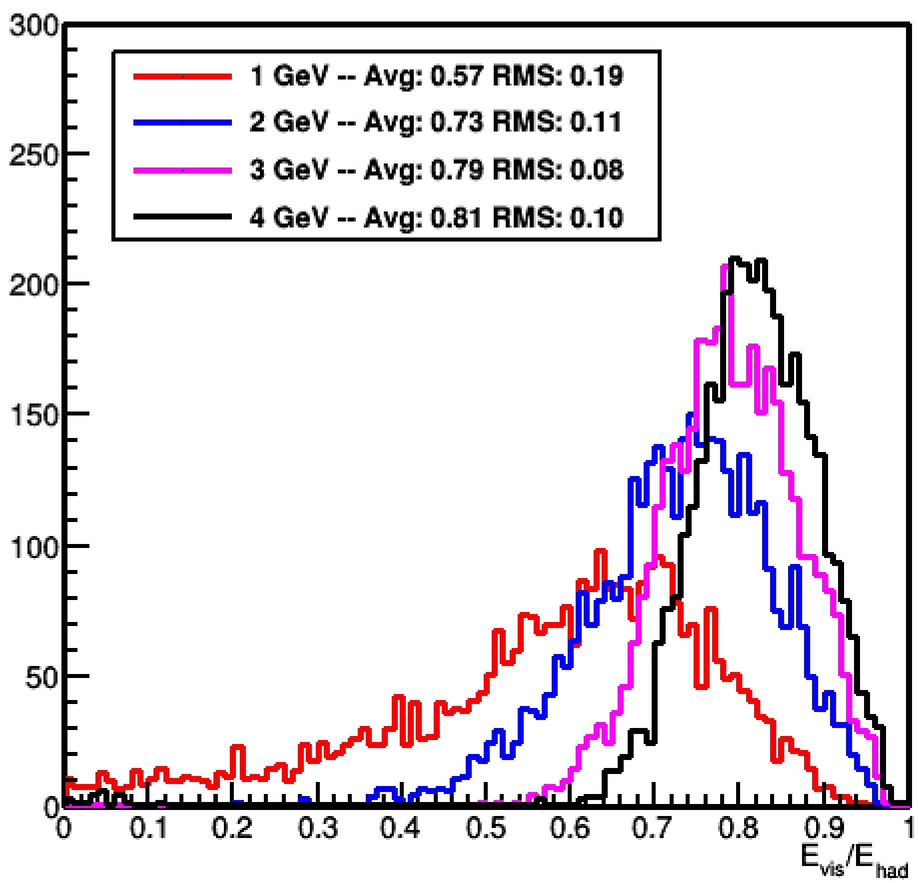
Muon Anti-neutrino



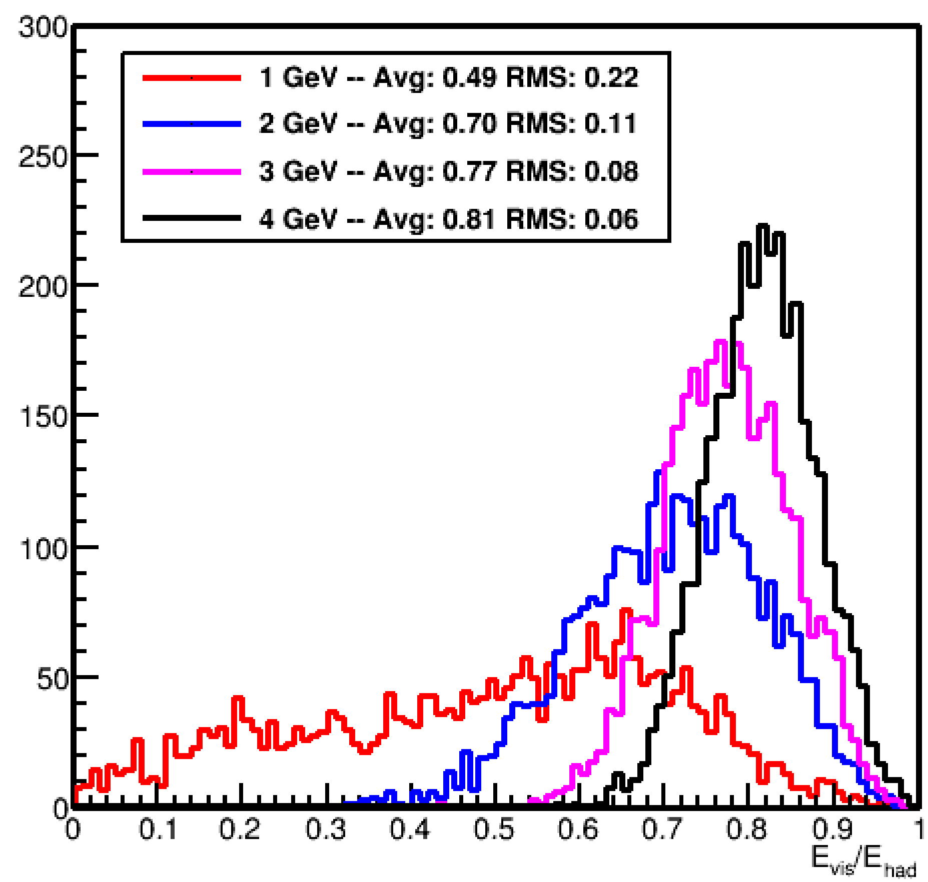
Fraction of E_{had} that is Visible

- The missing hadronic energy is mostly responsible for the missing visible energy.

Muon Neutrino



Muon Anti-neutrino



Conclusions and Summaries

- High resolution, unbiased neutrino energy reconstruction is needed for precision oscillation measurements.
  - Accurate neutrino energy reconstruction is not a simple problem
- Partial list of data needed to achieve required resolutions
  - For both:
    - Neutrino cross section measurements on Argon
      - μBooNE below 2 GeV
      - CAPTAIN @ NuMI above 2 GeV
  - For kinematic reconstruction:
    - Better neutrino cross section models
    - Leptons in Argon
      - LARIAT for e and μ
  - For calorimetric reconstruction:
    - Hadronic interactions in Argon
      - LARIAT for π and p
      - CAPTAIN for neutrons
- Covering the entire range of LBNE neutrino energy will need both kinematic and calorimetric reconstruction.